

The Spacecraft Water Impurity Monitor, a Framework for the Next Generation Complete Water Analysis System for Crewed Vehicles Beyond the ISS

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The Spacecraft Water Impurity Monitor (SWIM) is a joint collaboration to develop an instrument platform that will perform in-flight measurements and deliver a more complete picture of water quality to decision makers. Eventually, missions to the moon, Mars, and beyond will be equipped with analytical capabilities equaling those found in terrestrial labs. Based on what we know about current and future spacecraft environments, SWIM will seek to provide enhanced analytical capability that enables NASA to confidently send astronauts on distant missions without the possibility of returned water samples. This paper discusses the challenges presented by exploration requirements and the research and development progress toward the goal of a total water analysis system. For organic analysis, one of the analysis technologies that the SWIM team have been developing is a liquid-injection gas chromatograph mass spectrometer system; these systems are the workhorses of analytical chemistry laboratories world-wide. For inorganic analysis, the team is exploring a number of technologies ranging from traditional liquid chromatography technologies (e.g. ion chromatography, capillary electrophoresis) to flight-heritage technology such as ion-specific electrodes.

Nomenclature

<i>BGE</i>	= Background Electrolyte	<i>C⁴D</i>	= Capacitively Coupled Contactless
<i>BTEX</i>	= Benzene-Toluene-Ethylbenzene-Xylene		Conductivity Detection
<i>CE</i>	= Capillary Electrophoresis	<i>DAI-GC</i>	= Direct Aqueous Injection Gas Chromatograph

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<i>GC</i>	= Gas Chromatograph	<i>miniTOCA</i>	= miniature-TOCA
<i>ECLSS</i>	= Environmental Control and Life Support System	<i>OCEANS</i>	= Organic Capillary Electrophoresis ANalysis System
<i>EMILI</i>	= European Molecular Indicators of Life Investigation	<i>OTIC</i>	= Open Tubular IC
<i>ESI</i>	= Electrospray Ionization	<i>OWLS</i>	= Ocean Worlds Life Surveyor
<i>HPLC</i>	= High Performance Liquid Chromatograph	<i>OWM</i>	= Organic Water Module
<i>IC</i>	= Ion Chromatograph	<i>QITMS</i>	= Quadrupole Ion Trap Mass Spectrometer
<i>ICP-MS</i>	= Inductively-Coupled Plasma Mass Spectrometer	<i>S.A.M.</i>	= Spacecraft Atmosphere Monitor
<i>ILCESS</i>	= Ion Liquid Chromatograph for Solar System Exploration	<i>SBIR</i>	= Small Business Innovative Research
<i>ISE</i>	= Ion-Specific Electrode	<i>STTR</i>	= Small Business Technology Transfer
<i>ISS</i>	= International Space Station	<i>SWIM</i>	= Spacecraft Water Impurity Monitor
<i>LEO</i>	= Low Earth Orbit	<i>TCD</i>	= Thermal Conductivity Detector
<i>MS</i>	= Mass Spectrometer	<i>TOC</i>	= Total Organic Carbon
<i>MECA</i>	= Microscopy, Electrochemistry, and Conductivity Analyzer	<i>TOCA</i>	= Total Organic Carbon Analyzer
<i>MEMS</i>	= Micro-Electro-Mechanical Systems	<i>TDU</i>	= Technology Demonstration Unit
<i>MICA</i>	= Microfluidic Icy-World Chemistry Analyzer	<i>TMP</i>	= Turbo Molecular Pump
μ <i>FID</i>	= micro-Flame Ionization Detector	<i>UV-Vis</i>	= Ultraviolet-Visible
		<i>VCAM</i>	= Vehicle Cabin Atmosphere Monitor
		<i>VOC</i>	= Volatile Organic Compound
		<i>WPA</i>	= Water Processor Assembly
		<i>WCL</i>	= Wet Chemistry Lab
		<i>WRS</i>	= Water Recovery System

I. Introduction

ON-orbit analysis of the total organic carbon (TOC) content of recycled water, as provided by the ISS TOC Analyzer (TOCA)¹, has been an indispensable tool for monitoring the performance of the Water Recovery System (WRS) and for ensuring that water is fit for crew consumption. While TOC has been, and will continue to be an important metric for spacecraft water quality, it provides only limited insight into the total picture of water quality. As a measurement, TOC only provides a single “lump sum” quantity of all organic chemicals present in a water sample (as milligrams of carbon per liter of water); it neither identifies or quantifies the individual chemicals contributing to the TOC number. Nor does the TOC measurement begin to address inorganic constituents, be they undesired contaminants such as metals (e.g. nickel) resulting from corrosion of water system components, or an intentionally-dosed biocide such as silver or iodine. Because the ability to make comprehensive in-flight measurements of water quality has not existed for ISS, it has been the practice of NASA toxicologists and Environmental Control and Life Support System (ECLSS) managers to institute routine collection of water samples, and their subsequent return to earth for detailed laboratory analysis². For exploration missions beyond low Earth orbit (LEO), the return of water samples to Earth for analysis (like for the ISS), whether for routine checks or for troubleshooting problems with the life support system, will be logistically challenging or impossible. The need for development of in-flight water quality monitoring beyond TOC is captured in NASA Technology Roadmap TA 6.4.1, Sensors: Air, Water, Microbial, and Acoustic,^{3,4} specifically, 6.4.1.5 - water quality sensor to identify and quantify target organic and inorganic chemical species in the water of manned spacecraft without any reliance on ground analysis.

The Spacecraft Water Impurity Monitor (SWIM) is a collaboration between JPL, JSC and KBR to research and develop a modular instrument platform that will perform in-flight measurements and deliver a more complete picture of water quality to decision makers. Eventually, missions to the moon, Mars, and beyond will be equipped with analytical capabilities equaling those found in terrestrial labs. Based on what we know about the spacecraft environment, and the water produced by likely ECLSS architectures, SWIM will seek to provide enhanced analytical capability that enables NASA to confidently send astronauts on distant missions without the possibility of returned water samples.

This paper discusses the challenges presented by exploration requirements and the research and development progress toward the goal of a total water analysis system. For organic analysis, one of the analysis technologies that the SWIM team have been developing is a liquid-injection gas chromatograph (GC) / mass spectrometer (MS) system, called the Organic Water Module (OWM), to detect and identify dissolved VOCs in drinking water supplies^{5,6}. Liquid-injection GC/MS systems are the workhorses of analytical chemistry laboratories world-wide but have not flown before for space applications. The MS for OWM, a Paul quadrupole ion trap (QIT) MS, does have ISS flight heritage;

it was first used in the Vehicle Cabin Atmosphere Monitor (VCAM)⁷ in 2010 and is currently in use in the Spacecraft Atmosphere Monitor (S.A.M.)⁸. For inorganic analysis, the team is exploring a number of technologies that are currently funded by NASA. These technologies range from traditional liquid chromatography technologies such as ion chromatography and capillary electrophoresis to flight-heritage technology such as ion-specific electrodes (e.g. next-generation Wet Chemistry Lab⁹, originally part of the MECA instrument suite on the Phoenix spacecraft).

II. Modular Architecture and Technology Matrix

The Spacecraft Water Impurity Monitor (SWIM) aims to research, develop and deliver an instrument for identification and quantification of organic and inorganic impurities in spacecraft water. This instrument is expected to play a vital role in NASA’s human spaceflight missions beyond LEO, where sample return is impractical^{3,4,10}. Lunar Gateway, lunar surface, Mars transit, and Mars surface missions are all target end-users. It may be feasible, and even desirable, to fly a subset of our defined architecture as a tech demo as part of the chosen development path. However, this is only considered a means to an end – a step along the way to the ultimate SWIM platform. Depending on how such a subset is defined, there are real limitations that preclude such a system from being “equal to” the final instrument. The major example of such a limitation is the inherent lifetime of the vacuum system utilized by the S.A.M. Technology Demonstration Units (TDUs)⁸.

This option of demonstrating subunits of SWIM on the ISS (and, perhaps on NASA-funded commercial LEO space stations) has led to a modular approach to SWIM and its subsystems (Figure 1), not dissimilar to commercially-built analytical chemistry instrumentation used for liquid sample analysis. The SWIM architecture can be broken down in an Organic Water Module and an Inorganic Water Module, independent of each other but can be flown together if desired. Each of these main modules can be broken down farther into separation (if required) and detection modules. And, each separation module can be paired with one or more detection module dependent on mission, spacecraft, customer needs, and size/mass/power constraints.

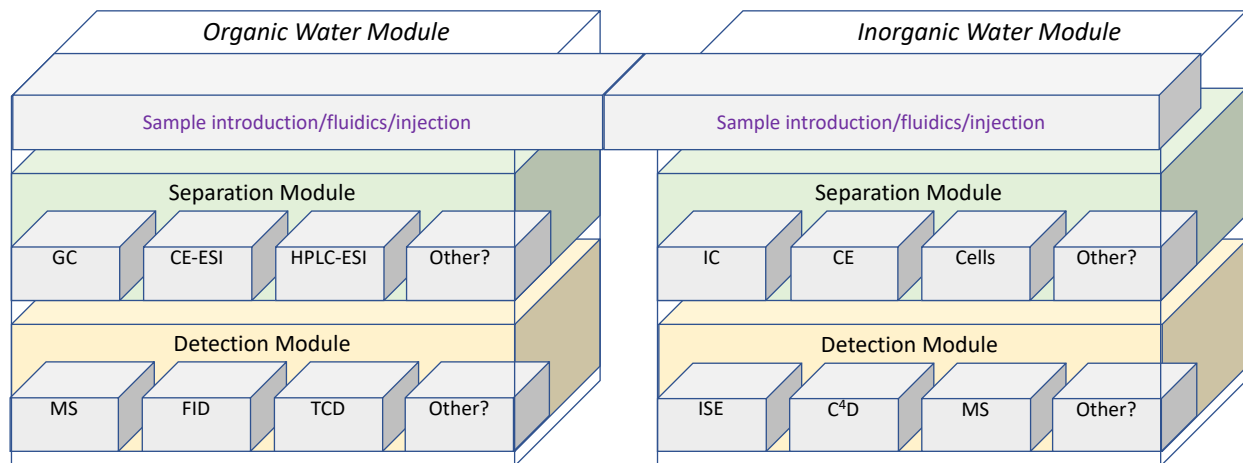


Figure 1. Modular approach to SWIM’s architecture. *The configuration of SWIM is dependent on mission, spacecraft, customer needs, and size/mass/power constraints.*

The SWIM team has been assembling a technology matrix populated with analytical chemistry technology typically used for water analysis on Earth but with an emphasis on NASA-funded (e.g. HEOMD-AES, SMD-ROSES, STMD-SBIR/STTR) projects. An overview of this matrix is in Table 1. It quickly becomes evident that much of the technology/techniques are gold-standard analytical chemistry instrumentation used to analyze drinking water worldwide, including by the Toxicology and Environmental Chemistry Laboratory at NASA Johnson Space Center¹⁰.

Many of these technologies do require consumables such as liquid and/or gas carrier fluids, calibrants, waste, etc. One operational scenario to consider for long-duration, isolated human spaceflight to save on consumables is the use a “triggering” philosophy of operation; for example, a rise in TOC as measured by the miniTOCA under development^{11,12} would trigger further analysis/identification by a liquid-injection GC/MS. Likewise for inorganics, a rise in conductivity as measure by an ISS-developed conductivity detector¹³ would trigger the use of an ion chromatograph, CE or ISE-array system.

A sampling of the NASA-funded technology that the SWIM team is currently developing are described in the following sections.

Table 1. SWIM Top-Level Technology Matrix. *It is modular with some systems utilizing one or more NASA-funded modules.*

Organic Water Module				
<i>Separation</i>	<i>Detection</i>	<i>Instrument Name(s)</i>	<i>NASA-funded</i>	<i>TRL</i>
Gas Chromatograph (GC)	Flame Ionization Detector (FID)	OWM	Yes	3-4
	Thermal Conductivity Detector (TCD)	OWM	Yes	3
	Mass Spectrometer (MS)	OWM/S.A.M	Yes	4-5
Capillary Electrophoresis (CE)	Electrospray Ionization (ESI)-MS	EMILI ¹⁴	Yes	4-5
	Conductivity	OCEANS ¹⁵	Yes	5
High Performance Liquid Chromatograph (HPLC)	UV-Vis or fluorescence	-	No	2
	ESI-MS	-	No	2
Inorganic Water Module				
<i>Separation</i>	<i>Detection</i>	<i>Instrument Name(s)</i>	<i>NASA-funded</i>	<i>TRL</i>
-	Ion-Specific Electrodes (ISEs)	MICA ¹⁶ /OWLS ^{17,18}	Yes	5
Ion Chromatograph (IC)	Capacitively Coupled Contactless Conductivity Detection (C ⁴ D)	ILCESS ^{19,20}	Yes	4
Capillary Electrophoresis (CE)	C ⁴ D	OWLS	Yes	5
Inductively-Coupled Plasma (ICP)	Mass Spectrometer (MS)	-	No	2

III. Organic Water Module

Organic contaminants in spacecraft cabin air and water present a unique challenge due to the ubiquity of potential sources, and the diversity of their chemical composition, structure, and behavior. Sources include outgassing from equipment (e.g. plastics, rubbers, fabrics, coatings), crew hygiene products (e.g. deodorants, lotions, wipes), and metabolic byproducts from the crew themselves. Once in the cabin environment, whether in the atmosphere or water, these contaminants can undergo chemical transformations and reactions, widening the scope of potential species. Fortunately, we know from experience that by the time contaminants make it into potable (WRS product) water, they usually are relatively small and simple molecules, making them volatile or semi-volatile.

SWIM research leverages multiple technologies from JPL and JSC/KBR. For analysis of volatile and semi-volatile organics, one of the analysis technologies that the SWIM team have been developing at JSC/KBR is a liquid-injection gas chromatograph (GC) / mass spectrometer (MS) system, historically called the Organic Water Module (OWM), to detect and identify dissolved VOCs in drinking water supplies. Liquid-injection GC/MS systems are the workhorses of analytical chemistry laboratories world-wide but have not flown before for space applications. The MS for OWM, a Paul quadrupole ion trap (QIT) MS, does have ISS flight heritage; it was first used in the Vehicle Cabin Atmosphere Monitor (VCAM)⁷ in 2010 and is currently in use in the Spacecraft Atmosphere Monitor (S.A.M.)⁸.

A. Liquid-Injection Gas Chromatograph

Monitoring of spacecraft potable water samples for the presence of volatile organic compounds such as acetone, methanol and ethanol as well as heavier organic compounds such as siloxanes and glycols will begin with injection into the SWIM gas chromatograph module. SWIM has been developing a direct aqueous injection gas chromatograph (DAI-GC) system capable of analyzing both classes of compounds in a single GC run. Figure 2 is a general schematic for the liquid injection and gas chromatograph portion of the system, with an example of the interface to the spacecraft. The water sample, either from the potable water bus or a sample bag, is injected using a multiport, internal sample loop valve. The spacecraft interface and sampling valve permits on-line analysis of the spacecraft water bus or a sample bag through the use of a sample pump. After injection, the sample is volatilized in the heated injector. SWIM is currently in the technology development phase for liquid injectors, and expects to select the final injector configuration later in the project life cycle. The compounds are separated in the GC column in the usual manner, and are currently detected by a thermal conductivity detector. The thermal conductivity detector is a useful device even when the final end-stage detector for the organics detection module, the QITMS, is present because it can aid in detecting when the water peak is eluting from the column. The system has means to isolate the mass spectrometer when the water is eluting from the column. The configuration show in Figure 2 is one of many possible candidates for the SWIM organics detection module, and technology development efforts over the coming years will help to finalize the organics detection architecture.

SWIM currently has breadboard-fidelity DAI-GC hardware running in the JSC AES Water Technology Development laboratory and has demonstrated the detection of both VOCs and heavier organics in a single GC run, using project-developed pneumatic controls and ground-station software. The Micro-Electro-Mechanical Systems (MEMS) thermal conductivity detector (TCD) control and readout electronics are also entirely project-developed, which allows for maximum future design flexibility. Any subsystem chosen for future use can then undergo any final development necessary to ensure flight readiness, using the early developments which were made already with an eye toward flight and use on manned spacecraft.

Figure 3 is a sample chromatogram from the system, showing detection of acetone, methyl ethyl ketone, methanol, ethanol, acetic acid, propylene glycol, and dimethyl sulfone in one GC run. The next step in SWIM development is interfacing the GC system with the QITMS, to build a DAI-GC-MS system. The addition of a mass spectrometer will provide increased sensitivity versus a thermal conductivity detector. A key benefit of having a mass spectrometer will be positive identification of compounds observed in the chromatogram by correlating the mass spectrum with the observed retention times.

B. Quadrupole Ion Trap Mass Spectrometer

The QITMS is identical to that used in S.A.M.²¹ It is a 3-D Paul Trap with a 10 mm field radius and effective capacitance of 85 pF. The trap is nominally operated using an 800 kHz rf voltage up to 2 kV in amplitude provided by a series resonant inductor (SRL) to the central ring electrode. The top and bottom endcaps are nominally kept at ground but, if desired, can be driven with arbitrary rf (180° out-of-phase) to provide secular excitation profiles to the trapped ions for further mass discrimination. These ion trapping parameters correspond to mass ranges up to 330 amu. At the center of both endcaps are two 1 mm OD x 2.5 mm long holes: one for the introduction of the electron beam and the second for the ejection of ions into the detector assembly. These small axial orifices have the added effect of transforming the trap volume into a pressure cell due the small 0.1 L/s

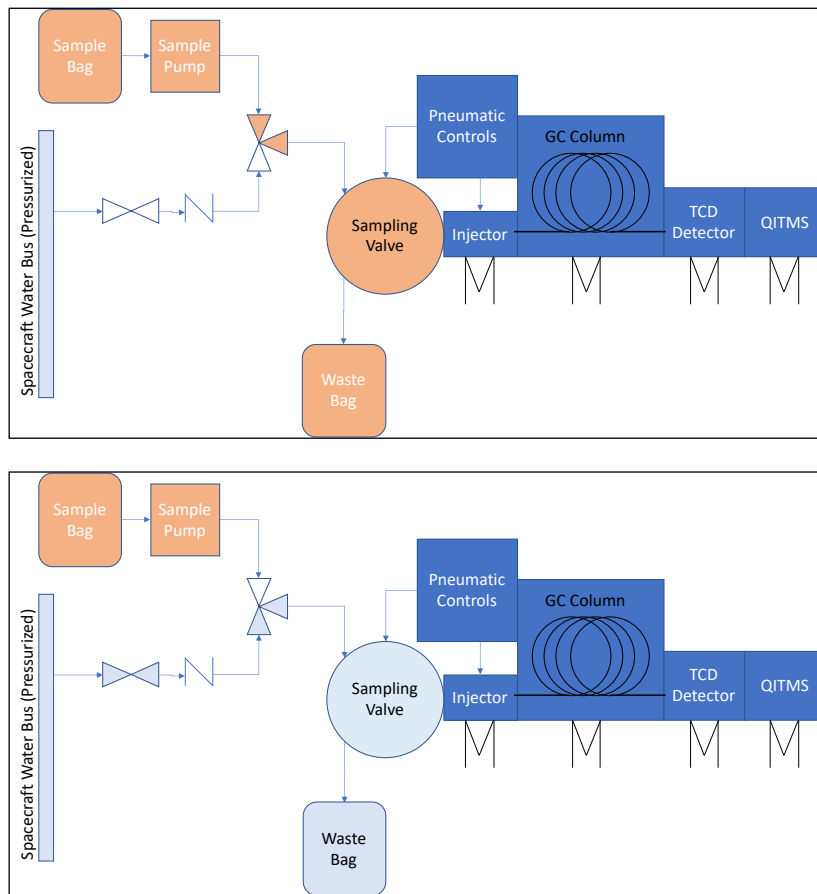


Figure 2. OWM's schematic for the liquid injection and gas chromatograph portion of the system. Top, sampling mode. Bottom, injection/chromatography modes.

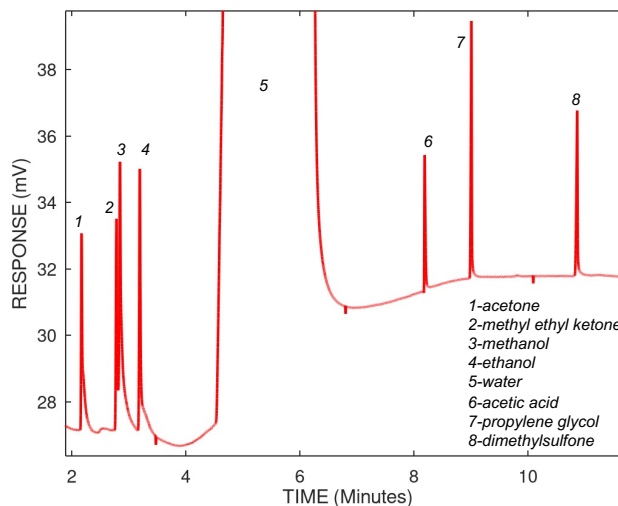


Figure 3. Sample chromatogram. TCD detection of acetone, methyl ethyl ketone, methanol, ethanol, acetic acid, propylene glycol, and dimethyl sulfone in one GC run.

effective conductance between the trap volume and the external vacuum chamber. Typical pumping speeds in the external chamber (~ 10 L/s) result in a 100-fold increase in pressure (and therefore ion count rates) in the QITMS trap volume. To prevent the creation of patch potentials due to the adhesion of trace organics on trap surfaces, the QIT is also coated with SilcoGuard[®] (SilicoTek[®]). To further maintain the cleanliness of trap surfaces, the QITMS is equipped with a 20 W halogen bulb which nominally heats the trap to above 200°C. The QITMS detector assembly consists of a channel electron multiplier (CEM - 5901 Burle Magnum, Photonis[®]) and two protection meshes called grids.

During the ionization period of the QITMS duty cycle, the two grids are elevated to -100 V and +100 V to prevent the negatively charged electron beam and positively charged ions from striking the CEM, which could otherwise result in decreased lifetimes due to oversaturation. During the q-scan rf ramp, both grids are lowered to ground allowing ejected ions to reach the CEM. Under nominal operation, the CEM is biased to -2.2 kV. Ion count rates are corrected for non-paralyzable dead times characteristic of this CEM type (~ 10 ns).

The QITMS assembly is housed in a 3D-printed titanium vacuum chamber (shown in Figure 4), which is intentionally designed to minimize the weight and footprint of the MS Sensor assembly. The additive manufacturing process (CalRAM, Carpenter Technology[®]) includes a state-of-the-art laser sintering procedure followed by hot isostatic pressing that reduces the porosity of the titanium to minimize outgassing and to increase its durability. After printing, the chamber undergoes traditional machining to clean out the internal volume as well as to create the knife edges for conflat flange seals. Ultimately these custom QITMS chambers exhibit external leak rates less than 10^{-11} Torr L/s and base pressures less than 10^{-10} Torr following a typical 24-hour bakeout at 150°C.

Due to the increased gas load expected from the liquid-injection GC, the QITMS is equipped with a Pfeiffer HiPace[®] 80 L/s turbomolecular pump (TMP) similar to what was flown on VCAM²². Keeping in-line with our modular approach to SWIM, if we have mass/power/size constraints, the QITMS can utilize S.A.M.'s ion-getter pump but at a lower duty cycle.

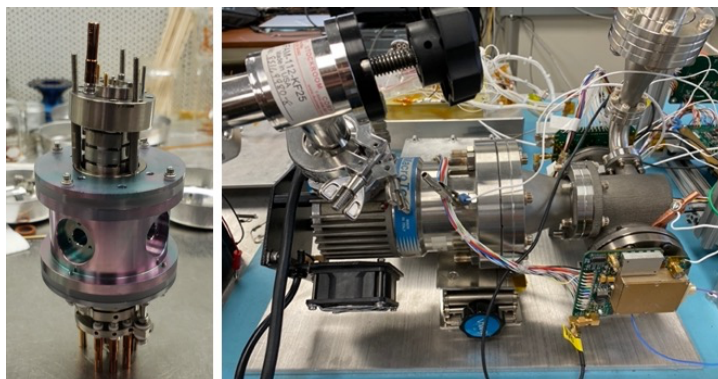


Figure 4. Flight-heritage quadrupole ion trap mass spectrometer. The QITMS on the left is a duplicate of the S.A.M. QITMS. One the right panel shows the S.A.M. 3-D printed titanium vacuum chamber (with the ion trap inside) coupled to the VCAM-heritage TMP.

C. Micro-Flame Ionization Detector

Originally an STTR project²³, we have been developing a portable gas sensor that consists of a micro-flame ionization detector (μ FID) and a micro-gas chromatograph (μ GC), which are integrated in a "lunch box" that has all the peripherals to operate micro-GC/FID without any external power and gas supply. Both micro-devices are now fabricated in JPL's Microdevices Laboratory using MEMS technology. The μ GC is now part of the preconcentrator/gas chromatograph subsystem of S.A.M.²⁴ and the μ FID (see Figure 5) has been re-purposed as a detection module for OWM.

We made the microburner using a Si wafer since smaller burner cavities can be more easily made using microfabrication technologies in Si than normal machining needed for Macor, easier manufacturing of smaller feature size with a lower tolerance, total cost reduction using batch process for mass production. A standard Si wafer was used to make the burner structure. We made a silicon-on-insulator (SOI) wafer by fusion bonding of two 500 μ m thickness wafers. Each wafer has 2 μ m thickness of oxide. Buried oxide serves as electrical isolation between two Si layers to avoid the short. After successful bonding of the two wafers, the same pattern as in the Macor

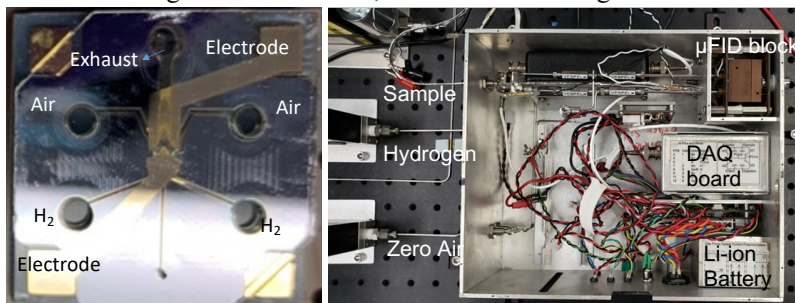


Figure 5. Micro-flame ionization detector. Left, the μ FID chip; on the right is the μ FID module.

microchannel was made and etched using ICP-DRIE. Finally, a thermal oxide was grown over entire device for 13.5 hrs at 1100°C. To obtain the flame shape, we used an Au melted profile by the flame on plane Au-sputtered Quartz plates. The same technique was used for the (a) metal electrode (Cr/Au = 100 Å/1000 Å) beneath the modified Macor burner taking into consideration the flame's shape and location; and (b) two metal electrodes sandwiching the Macor burner. The μ FID features exceptional sensitivity over 40 mC/gC with a detection limit of less than 8 ng hexane. BTEX and various hydrocarbon compounds at the level of nano grams were also separated and detected.

IV. Inorganic Water Module

To date, the only technology deployed for inorganic monitoring of drinking water on the ISS is the Conductivity Sensor on the WPA (Water Processing Assembly)¹³. Therefore, for more detailed inorganic analysis, the team is exploring a number of technologies at JPL that are currently funded by NASA. These technologies range from traditional liquid chromatography technologies, such as ion chromatography and capillary electrophoresis, to flight-heritage technology such as ion-selective electrodes.

A. Ion-Selective Electrodes

Ion selective electrodes (ISEs) are a well-established tool of analytical chemistry most widely used in routine blood analysis²⁵. NASA used them to measure the soluble properties of the Martian regolith on the Phoenix mission. ISEs were part of the Wet Chemistry Lab (WCL), one subsystem of the Microscopy, Electrochemistry, and Conductivity Analyzer (MECA) instrument⁹. WCL made the most surprising discovery of the Phoenix mission when it found significant quantities of perchlorate salts in the regolith²⁶, and demonstrated the power of ISEs for identifying unexpected compounds.

Since Phoenix NASA has continued to fund ISE sensors and sensor array instrument development work to further miniaturize the system and expand the list of measurable targets. One of the most recent efforts is the Microfluidic Icy World Chemical Analyzer (MICA) developed for inclusion on a potential Europa Lander mission (Figure 6)¹⁶.

MICA has taken the next step in ISE sensor technology by making use of nanocarbon based solid contact ISEs instead of the hydrogel based sensors used in WCL²⁷. This has allowed for a reduction in size of the sensors (and their arrays) as well as moving from a beaker style measurement to a fluidic channel. This reduces the volume needed for analysis by $\geq 100\times$, from 25 mL down to ≤ 250 μ L. Additionally, MICA includes Eh, conductivity, and voltammetry electrodes to measure other fundamental properties of the solution that area also relevant to SWIM. MICA also takes advantage of NASA's significant investment in microfluidics for space biology experiments, leveraging the miniaturized technology developed for multiple CubeSat missions²⁸⁻³⁰. In general the electrochemical sensor array approach has the benefit that it is easily scalable based on the number of targets desired. A minimal instrument that measured conductivity, as well as had ISEs for pH and silver concentrations would require few resources. However,

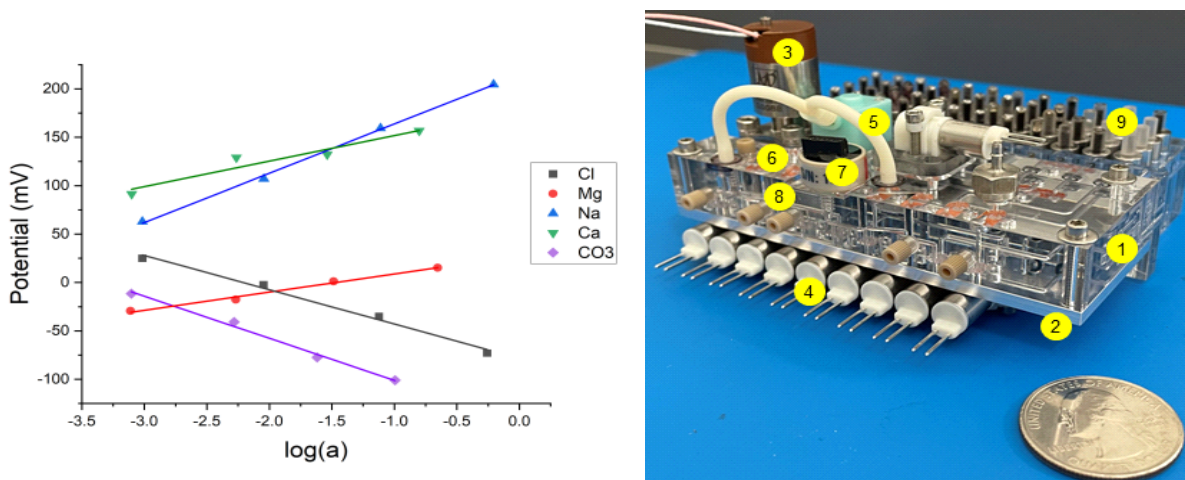


Figure 6. The MICA instrument. Left, calibration plots for a selection individual ISEs. Right, Photo of MICA fluidic system with: 1) fused 3-layer manifold; (2) thermomechanical backing plate; (3) hermetic microvalve; (4) fluid-control valves; (5) peristaltic pump; (6) fluid-in-channel feed-through (AC conductivity); (7) pressure sensor; (8) liquid connectors; (9) 48-electrode array.

even MICA, a fully populated array capable of targeting a wide variety of anions and cations is compatible with a 2 – 3 U CubeSat-style package.

B. Ion Chromatograph with Conductivity detection

Motivated by WCL's detection of perchlorate on Mars, development of more capable ion detection instruments followed the Phoenix mission as well. Ion chromatography (IC) is an industry standard for water quality monitoring of municipal systems as well as in the pharmaceutical and semiconductor industries³¹. Traditional IC uses packed chromatography columns made up of functionalized resin/particles in the 2 – 25 μm size range. The disadvantages of packed column chromatographic columns for space applications are that they require large high pressure pumps needed to generate flow through the small pores between the particles, and that temperature extremes or periods of dryness have the potential to disturb the packing of the column itself (channeling) leading to reduced performance.

To circumvent these challenges open tubular IC (OTIC) approaches were funded by NASA. OTIC uses a narrow diameter capillary (10 – 30 μm) with a functionalized surface as the chromatographic column. This drastically reduces the pressure required for separations (~ 10 s of PSI) and makes the column more robust to different environmental and operations conditions. All of the critical functional components of an IC system including eluent generation, sample injection, the column, background suppression, and conductivity detection have been matured to allow commercial system level performance from an OTIC system³²⁻³⁵. Currently, the Ion/Liquid Chromatograph for Exploration of the Solar System (ILCESS) project is working to mature the TRL of an OTIC system for planetary applications.

ILCESS (Figure 7) has focused primarily on anion chromatography, motivated by the desire to unravel the chlorine speciation of Mars (chloride, chlorate, and perchlorate) as well as to look for relevant markers of habitability including nitrite/nitrate and small organic acids like formate, acetate, and benzoate. However, adaptation of the system to also measure cations via the inclusion of a cation column has been demonstrated in the literature³⁶.

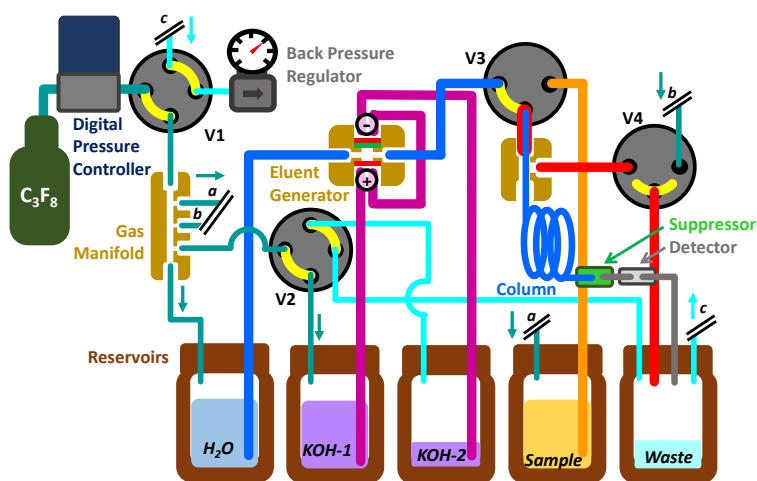


Figure 7. The ILCESS instrument. Schematic of the Ion Liquid Chromatograph for Solar System Exploration (ILCESS).

C. Capillary Electrophoresis with Conductivity detection

Capillary electrophoresis (CE) is another high efficiency separation method that is well established for small ion analysis³⁷. NASA funded work initially focused on amino acids for life detection missions³⁸, but has recently branched out into capacitively coupled contactless conductivity detection (C⁴D) as well with methods broadly applicable to both anions and cations of potential relevance to water systems^{39,40}. A method was even developed for the detection of silver and other metals at ISS relevant levels as a direct example of what type of performance a system like this could have as part of the SWIM architecture⁴¹.

CE is an attractive approach because of its simplicity and flexibility. Its simplicity is that it only requires a standard glass capillary filled with a conductive background electrolyte (BGE) to allow the establishment of an electrical circuit and electrophoretic separation of any charged species. Its flexibility is that by simply changing the BGE a wide variety of different methods targeting different compound classes can be achieved.

A complete prototype (Figure 8) of the Organic Capillary Electrophoresis ANalysis System (OCEANS)¹⁵ has been developed and demonstrated as part of both the EMILI¹⁴ project and another life detection instrument suite; Ocean Worlds Life Surveyor (OWLS)^{17,18}. The OCEANS prototype demonstrates performance identical to that of commercial analyzers⁴² using a number of different detectors including C⁴D. Separately, a C⁴D detector design that restricted itself to a flight migratable EEE parts selection, was also built and tested demonstrating equivalent performance to commercial detectors while also being suitable for flight⁴³.

Cations	Anions	Metals
Sodium	Chloride	Silver
Potassium	Nitrate	Nickel
Magnesium	Sulfate	Zinc
Calcium	Chlorate	
Lithium	Perchlorate	
Ammonium	Phosphate	

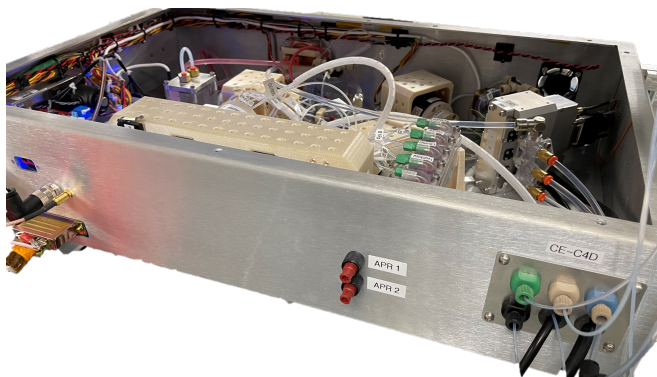


Figure 8. The CE-C⁴D instrument. Left, a table of inorganic species already demonstrated by the CE-C⁴D system. Right, an image of the field portable CE-C⁴D system with its cover off.

V. Plan Forward

The Spacecraft Water Impurity Monitor (SWIM) is a collaboration between JSC, JPL and KBR to develop an instrument platform that will perform in-flight measurements, delivering a more complete picture of water quality to decision makers. Eventually, missions to the moon, Mars, and beyond will be equipped with analytical capabilities equaling those found in terrestrial labs. For NASA's immediate exploration goals, this lofty vision is clearly impractical. Rather, these capabilities must be developed and implemented in an incremental and strategic fashion, with emphasis placed on the most impactful measurements first. Based on what we know about the spacecraft environment, and the water produced by likely ECLSS architectures, SWIM will seek to provide enhanced analytical capability that enables NASA to confidently send astronauts on distant missions without the possibility of returned water samples. This enhanced capability will be balanced with the challenges of mass, power, volume, schedule, and budget constraints that will be faced by any exploration mission.

SWIM is currently in a research and development phase, primarily identifying technologies that could adequately analyze organic and inorganic components of an ECLSS potable water and might have a path-to-flight. We will continue to leverage and combine NASA-funded technologies to provide the broadest flexibility in future enhanced water-monitoring capabilities.

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